

SUB- L^* GALAXIES AT REDSHIFTS $z \sim 4$, 3, AND 2: THEIR UV LUMINOSITY FUNCTION AND LUMINOSITY DENSITY

MARCIN SAWICKI

Department of Physics, University of California, Santa Barbara, CA 93111, USA
sawicki@physics.ucsb.edu

DAVID THOMPSON

Caltech Optical Observatories, California Institute of Technology, Pasadena, CA 91125, USA
djt@iraastro.caltech.edu

Abstract. We use very deep ($\mathcal{R}_{lim}=27$) U_nGRI imaging to study the evolution of the faint end of the UV-selected galaxy luminosity function from $z \sim 4$ to $z \sim 2$. We find that the luminosity function evolves with time and that *this evolution is differential with luminosity*: the number of sub- L^* galaxies increases from $z \sim 4$ to $z \sim 3$ by at least a factor of 2.3, while the bright end of the LF remains unchanged. Potential systematic biases restrict our ability to draw strong conclusions at lower redshifts, $z \sim 2$, but we *can* say that the number density of sub- L^* galaxies at $z \sim 2.2$ is *at least* as high as it is at $z \sim 3$. Turning to the UV luminosity density of the Universe, we find that the luminosity density starts dropping with increasing redshift already beginning at $z=3$ (earlier than recently thought — Steidel et al. 1999) and that this drop is dominated by the same sub- L^* galaxies that dominate the evolution of the LF. This differential evolution of the luminosity function suggests that *differentially* comparing key diagnostics of dust, stellar populations, etc. as a function of z and L should let us isolate the key mechanisms that drive galaxy evolution at high redshift.

1 Introduction

The shape of the galaxy luminosity function (LF) bears the imprint of galaxy formation and evolutionary processes. In particular, the presence of a break at the characteristic Schechter luminosity L^* , suggests that galaxies below L^* differ substantially from those above it. Because of this, our understanding of how galaxies form and evolve may profit from studying the evolution of not just the bright but also the faint members of the galaxy population at high redshift. To date, the faint end of the luminosity function at high redshift has only been studied using single deep but small fields that do not provide sufficient galaxy numbers or insurance against cosmic variance to give trustworthy LF measurements. And yet, for any reasonable faint-end slope of the LF, it is exactly these poorly-studied faint galaxies that not only dominate the number counts, but also contribute most of the cosmic luminosity density. With these facts in mind, we have set out to study the statistics of faint, sub- L^* galaxies at high redshift.

2 The Keck Deep Fields survey

We study the global statistics of sub- L^* galaxies at high redshift using a very deep imaging survey that utilizes the very same U_nGRI filter set and color-color selection techniques as are used for brighter galaxies in the work of Steidel et al. (1999, 2003, 2004). In contrast to the Steidel et al. work, our survey reaches $\mathcal{R}_{lim}=27$; this is 1.5 magnitudes deeper than Steidel et al. and significantly below L^* at $z=2-4$ (Sawicki & Thompson, 2005). These Keck Deep Fields (KDF) were obtained with the LRIS imaging spectrograph on Keck I and represent a total of 71 hours of integration. The KDF have an area of 169 arcmin² divided into 3 spatially-independent patches. This arrangement allows us to monitor the effects of cosmic variance on our results.

Our use of the U_nGRI filter set lets us select high- z galaxies using the color-color selection criteria defined and spectroscopically tested by Steidel et al. (1999, 2003, 2004). We can thus confidently select sub- L^* star-forming galaxies at high redshift without the need for spectroscopic characterization of the sample — characterization that would be extremely expensive at the faint magnitudes that interest us. Moreover, this commonality with the Steidel et al. surveys permits us to robustly combine our data with their, thereby for the first time consistently spanning a large range in galaxy luminosity at high redshift.

To $\mathcal{R}=27$, the KDF contains 427, 1481, 2417, and 2043, U_nGRI -selected star-forming galaxies at $z \sim 4$, $z \sim 3$, $z \sim 2.2$, and $z \sim 1.7$, respectively, selected using the Steidel et al. (1999, 2003, 2004) color-color selection criteria (Fig. 1). A detailed description of the Keck Deep Field observations, data reductions, and high- z galaxy selection can be found in Sawicki & Thompson (2005a).

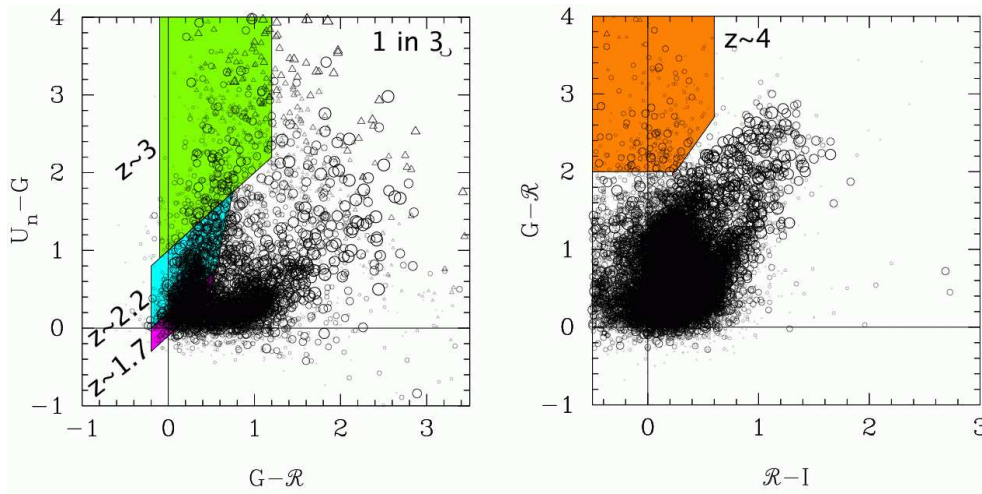


Figure 1: Color-color diagrams illustrating the Steidel et al. criteria we use for selecting high- z samples in the KDF. The left-hand panel illustrates selection of $z\sim 3$, 2.2, and 1.7 samples and the right-hand panel shows the selection of $z\sim 4$ galaxies. For clarity, in the left-hand panel we plot only one third of the objects present in our catalog. The filters we used and our color selection are *both* identical to those used by the Steidel team to select galaxies at $z\sim 1.7\text{--}4$. However, our data reach to $R=27$, or 1.5 magnitudes deeper.

3 Measuring the luminosity function

Figure 2(a) shows the luminosity function of UV-selected star-forming galaxies at $z\sim 4$, 3, and 2.2. At $z\sim 4$ and 3, we augment our KDF data with the identically-selected Steidel et al. (1999) galaxy count measurements at bright magnitudes, $R < 25.5$. Following Steidel et al. (1999), our LF calculation uses the effective volume technique, computing V_{eff} through recovery tests of artificial high- z galaxies implanted into the imaging data. Our analysis includes a comprehensive study of a variety of potential systematic effects (see Sawicki & Thompson 2005b for details) and consequently we can be confident about the robustness of our LFs. When such robustness is lacking — as it is at $z\sim 2$ — we know not to overinterpret our results.

As Fig. 2(a) shows, our data reach very faint luminosities which correspond to star formation rates of only $1\text{--}2 M_\odot/\text{yr}$ (not corrected for dust). Until now, LF measurements at these depths have only been carried out in small, single deep fields (such as the HDFs) and so are subject to small number statistics and/or vagaries of large scale structure (e.g., Sawicki, Lin, & Yee 1997; Gabasch et al. 2004). Moreover, until now it was necessary to combine these faint-end data with bright-end results that had been selected using different selection criteria — an approach fraught with potential biases. And finally, hitherto little attention has been paid to potential systematic effects in high- z LF measurements. In contrast, our KDF results are the deepest and most robust LF measurements at these redshifts and, very importantly, can readily and straightforwardly be combined with the Steidel et al. (1999) results at the bright end.

Our $z\sim 4$ and $z\sim 3$ LFs are very insensitive to a large range of systematics, although the $z\sim 2.2$ and $z\sim 1.7$ LFs are more uncertain. Specifically, the $z\sim 1.7$ LF is likely quite strongly affected by systematics (see Sawicki & Thompson 2005b for details) and so we do not discuss it here. Our $z\sim 2.2$ LF measurement is probably also affected by systematics but to a smaller degree than the $z\sim 1.7$ LF: we can confidently state that the number density of $z\sim 2.2$ galaxies is *not lower* than shown in Fig. 2(b), and that if it is higher than the LF shown, it is so by no more than a factor of ~ 2 . The $z\sim 3$ and $z\sim 4$ LFs are very robust against systematics as verified by a range of tests (Sawicki & Thompson 2005b).

The values of Schechter function parameters are given in Sawicki & Thompson (2005b) and here we only note that our $M^* \sim -21$ at $z\sim 4$ and $z\sim 3$ and also that we find shallower faint-end slopes than found by Steidel et al. (1999) using HDF-N data. Specifically, Steidel et al. (1999) found $\alpha = -1.6$ at $z\sim 3$ in the HDF-N (and in the absence of good statistics, had to *assume* the same $\alpha = -1.6$ value for $z\sim 4$). Our KDF analysis, which uses much larger datasets that span several spatially independent fields, finds $\alpha = -1.43$ at $z\sim 3$ and $\alpha = -1.26$ at $z\sim 4$. Workers who still use the Steidel et al. (1999) HDF-N value to extrapolate the contributions of sub- L^* galaxies from bright galaxy counts at higher redshifts should take note of these more accurate, shallower faint-end slopes. The new, shallower faint-end slopes we find have a significant effect on estimates of the luminosity density of the Universe (see § 5).

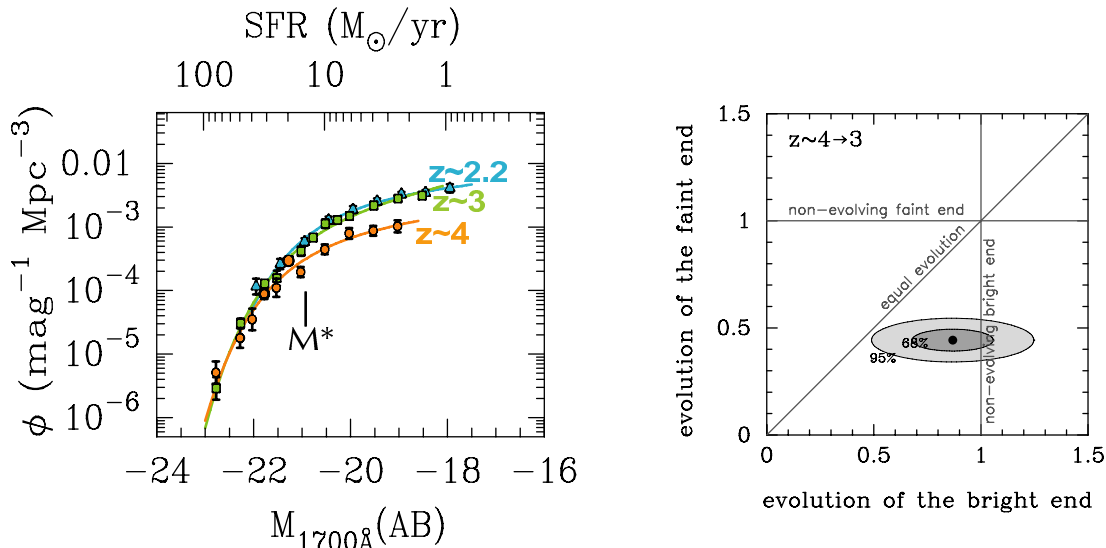


Figure 2: **(a) Left panel:** Evolution of the UV luminosity function. The $z\sim 4$ and $z\sim 3$ LFs are robust against a range of possible systematics and the evolution between these two epochs is real. The $z\sim 2.2$ LF may be subject to a systematic bias — the $z\sim 2.2$ LF shown here is the *lower limit* on the number density of galaxies. At $z\sim 4$ and $z\sim 3$ the KDF data are complemented by data from Steidel et al. (1999) at the bright end ($M < M^*$ at $z\sim 4$ and $M < M^* + 1$ at $z\sim 3$). The errorbars include both root-N statistics and field-to-field variance estimated through bootstrap resampling. **(b) Right panel:** The luminosity dependent evolution of the number density of galaxies from $z\sim 4$ to $z\sim 3$. The horizontal axis shows the change in the number density of luminous galaxies ($M_{1700} < -21$) between $z\sim 4$ and $z\sim 3$. The vertical axis shows the evolution for low-luminosity galaxies, ($M_{1700} > -21$). Three fiducial evolutionary scenarios are shown using solid lines: no faint-end evolution (horizontal line), no bright-end evolution (vertical line) and equal evolution at the bright and faint ends (diagonal line). There is substantial evolution of the low-luminosity population from $z\sim 4$ to $z\sim 3$ and the differential evolution scenario is statistically significant at the 98.5% level.

4 Differential evolution of the luminosity function

The luminosity function of high- z galaxies undergoes evolution that is differential with luminosity. As Fig. 2 shows, we find a factor of ~ 2.5 evolution in the number density (or, alternatively, 2 mag in luminosity) of *faint*, sub- L^* Lyman Break Galaxies between $z\sim 4$ to $z\sim 3$. At the same time, there is no evidence for evolution of the bright end of the LF.

Our tests show that it is highly unlikely that the observed differential evolution is due to some systematic effect such as selection bias, our modeling of the survey volume, etc. (see Sawicki & Thompson 2005b for a detailed discussion). The effect is also statistically quite significant — the probability that the evolution is not differential with luminosity is only 1.5% (see Fig. 2(b)). We therefore conclude that the differential, luminosity-dependent evolution is very likely real. If so, it must reflect some real intrinsic evolutionary differences between faint and luminous LBGs. Understanding what these differences are will give us insights into what drives galaxy evolution at high redshift.

5 The UV luminosity density of the Universe

The importance of the faint end of the luminosity function extends into measurements of the cosmic luminosity density and its derivative, the cosmic star formation rate. As is illustrated in Fig. 3(a), for observed values of the faint-end slope α the bulk of the luminosity density resides in galaxies that are fainter than L^* . Attempts to measure the contribution of the low-luminosity galaxies have been made previously using single small fields (e.g., Madau et al. 1996; Sawicki, Lin, & Yee, 1997; Steidel et al. 1999; Gabash et al 2004). But it is only with a deep, multi-field and large-area survey such as the KDF that we can robustly measure the contribution of these dominant galaxies to the total luminosity density.

Figure 3(b) shows a compilation of UV luminosity density values that trace the evolution of the luminosity density from $z\sim 5$ to the present. The black symbols show the total luminosity density, obtained by integrating the luminosity-weighted luminosity function over *all* luminosities. The total luminosity density exhibits a strong increase from $z\sim 5$ to $z\sim 3$ followed by the well-known strong decline below $z\sim 1$. At present, it is not yet clear if there is a plateau at $z\sim 3-2$ since, as mentioned in § 3, our $z\sim 2$ points are strictly speaking lower limits.

It is interesting to ask which galaxies contain the bulk of the UV light and — presumably — star formation

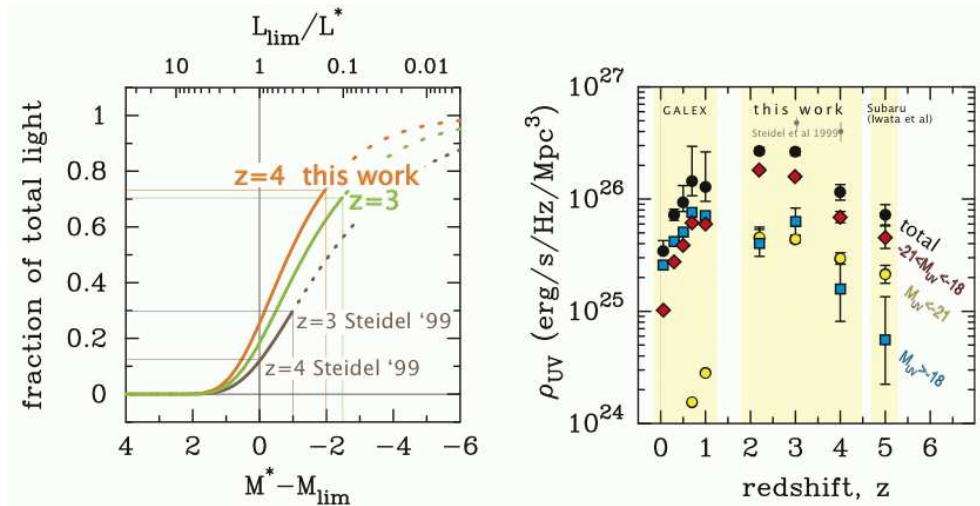


Figure 3: **(a) Left panel:** The fraction of total light captured by integrating the luminosity function down to a limiting magnitude M_{lim} . The curves are computed by integrating the luminosity-weighted Schechter function with parameters derived by Steidel et al. (1999; blue curves) and by our analysis (orange and green curves). Steidel et al. ground-based surveys capture only a small fraction of the light produced by Lyman Break Galaxies. In contrast, the KDF are sufficiently deep to capture 75-80% of the UV light present at these redshifts. **(b) Right panel:** The UV luminosity density of the Universe. Solid black symbols show the total luminosity density, while the colored symbols show the luminosity density that resides in galaxies split by luminosity range. The low- z points are due to GALEX (Arnouts et al. 2005; Schiminovich et al. 2005; Wyder et al. 2005) where we used their results to calculate values for our three luminosity sub-ranges; we calculated the $z \sim 5$ points by integrating the LF of Iwata et al. (2005) based on deep Subaru imaging. The values obtained by integrating the Steidel et al. (1999) LFs (with their $\alpha = -1.6$) are also shown for comparison. This figure shows that the bulk of the UV luminosity density at high redshifts comes from galaxies in the range $-21 < M < -18$ (red diamonds). These are exactly the sub- L^* galaxies that are probed by the KDF and are also the galaxies responsible for the rapid rise of the luminosity density from $z \sim 5$ to $z \sim 3$.

at each redshift. The colored points in Fig. 3(b) show the contributions to the total luminosity density that are made by galaxies in three luminosity ranges (split at $M = -21$ and $M = -18$). As the red diamonds show, the *bulk* of the luminosity density at high redshift comes from intermediate-luminosity galaxies between $M_{z \sim 3,4}^* + 3$ and $M_{z \sim 3,4}^* + 3$. Galaxies that are brighter than $M = -21$ ($\approx M^*$) as well as those fainter than $M = -18$ ($\approx M^* + 3$) contribute little to the total luminosity density at high redshift. The galaxies that dominate the luminosity density come from just a small range of luminosity just below L^* and are exactly the galaxies probed by the KDF.

6 What drives the evolution of the sub- L^* galaxies?

The steep increase in the luminosity density at high redshift is due to the increase in the number density of sub- L^* galaxies and the resulting steepening of the LF's faint-end slope α . However, as Fig. 2 illustrates, while the number density of sub- L^* galaxies increases with time, the number of luminous ones remains constant. This differential evolution must reflect important evolutionary differences between luminous and faint galaxies at these redshifts. Understanding the mechanism that underlies this differential, luminosity-dependent evolution will teach us important lessons about how galaxies form and evolve.

At present, it is not clear what is responsible for the observed differential evolution of the LF. One straightforward possibility is that the number of faint (but not bright) LBGs simply increases over the 600 Myr from $z \sim 4$ to $z \sim 3$. If UV luminosity reflects underlying mass, such an increase could be a reflection of an evolutionary trend that favors star formation in progressively lower-mass systems as the Universe ages (see, e.g., Iwata et al. 2005). Another possibility is that dust properties — its amount or covering fraction — may be decreasing in faint LBGs with time. Such a change would make individual faint galaxies brighter and thus would steepen the faint end of the LF. Yet another possibility is that if star formation in individual faint LBGs is episodic (e.g., Sawicki & Yee 1998), then they may brighten and fade (and thus move in and out of a given magnitude bin in the LF) with duty cycle properties that change with redshift. Longer or more frequent star-forming episodes would then result in a steeper luminosity function.

Whatever the mechanism, the fact that the LF evolution is differential suggests that different evolutionary mechanisms are at play as a function of UV luminosity. Studies that *differentially* compare key galaxy properties as a function of luminosity and redshift should help us isolate the mechanisms that are responsible for this

evolution. Such studies, including comparisons between spectral energy distributions or clustering properties of galaxies as a function of luminosity are already underway. A key point here is that we have identified luminosity and redshift as important variables in galaxy evolution at high z . While LBG follow-up studies to date have primarily focused on luminous galaxies, extending such studies to cover a range of luminosity that spans the break “knee” of the luminosity function will yield valuable insights into how galaxies form and evolve.

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